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Secondary Control for Reactive Power Sharing in Droop-Controlled Islanded MicroGrids

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Abstract — This paper focuses on the islanded operation of microgrids. In this mode of operation, the microsources are required to cooperate autonomously to regulate the local grid voltage and frequency. Droop control is typically used to achieve this autonomous voltage and frequency regulation. However, droop control has real and reactive power sharing limitations when there are mismatches between the microsources. This paper analyses the effect due to mismatches in the power line impedances connecting the source inverters to the microgrid. From the simulations results obtained, it was shown that the reactive power demand is unequally shared between the microsource inverters when there are mismatches between the power line impedances. To achieve equal reactive power sharing between the inverters, an external loop requiring low bandwidth communications was implemented in a central controller. Simulation results are presented showing the feasibility of the proposed solution in achieving reactive power sharing between the inverters connected to the microgrid.

Keywords - microgrids, reactive power sharing, low bandwidth communication, islanded operation

I. INTRODUCTION

The recent shift in paradigm towards the decentralization of electricity generation has effectively increased the penetration of distributed generation (DG). Microgrids are becoming an important concept to integrate DG and distributed energy storage systems [1]. When paralleling multiple inverters, that are capable of operating in both grid connected and islanding mode, a droop control scheme [1 - 4] is typically used in which the voltage and frequency of each inverter are adjusted in order to control active and reactive power. Droop control employs locally measured variables to achieve equal p.u. real and reactive power sharing when operating in islanded mode. However, mismatches in the inverter physical parameters and in the power line impedances that connect the inverters to the PCC degrade the power sharing accuracy. The additional reactive currents supplied by the inverters due to the unequal sharing do not allow the inverters to supply the maximum allowable real power.

Inverters operating in islanded mode share the reactive power demand by measuring the voltage at their respective PCC and determine the output voltage magnitude required as a function of the reactive power. However, due to line

impedance mismatches, the voltage at the PCC of each inverter is not equal. Hence, equal reactive power sharing cannot be achieved as the voltage droops settle at different values. On the other hand, the real power sharing capabilities are not affected by line impedance mismatches, as the frequency at steady state is constant throughout the whole microgrid. The additional reactive current supplied by each inverter reduces the maximum real power that can be supplied by the inverters.

Equal sharing of linear and non-linear loads has been investigated in literature. The authors in [5] tackle the reactive power mismatches that arise from mismatches between the inverter output interface inductors. This is done by an additional integral controller that regulates the voltage at the PCC to follow that of a set reference (removing the steady state error). Although such a technique is suitable for the mismatches in the inverter parameters it does not compensate for line impedance mismatches. The inverters have different PCC voltages due to the mismatch in the impedances and thus the integral term cannot compensate for an error which it cannot identify. In [6], Zhong investigates the unequal load sharing in resistive microgrids. In such grids, reverse droops (voltage and frequency of each inverter are adjusted in order to control reactive and active power) are preferred instead of traditional droops. In these grids, unequal voltage outputs by the inverters are seen to affect the equal real power sharing. However, the frequency is constant throughout the microgrid, reactive power is shared equally. The authors introduce an adjustment to droop control similar to [5] which however still does not account for line mismatches. The authors in [7] propose that the reactive power sharing can be improved by adjusting the voltage droop gains so as to incorporate the line impedance effects. The authors assume that the inductive impedance of the virtual impedance loop is large enough to make the line impedance negligible. However simulations carried out have shown that even if an actual inductance is connected at the output, the choice droop gain by itself does not compensate for the line impedance mismatches and unequal sharing still occurs. The authors in [8] propose a new droop control method to compensate for line parameter mismatches in which the reactive power is controlled in proportion to the derivative of the voltage. Although this method reduced the mismatch in the reactive power supplied

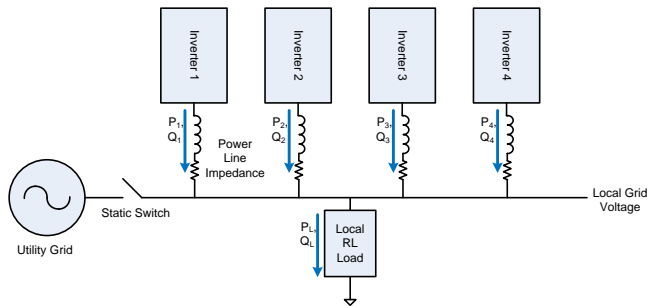


Fig. 1. Microgrid Hardware Setup

by parallel connected inverters, it did not achieve equal sharing while adding to the complexity of the control algorithm.

Various literatures promote the use of a central controller that optimizes the operation of droop control through non-critical communications. In such cases, the microgrid can still function properly should communication from the central controller fail to occur, although not at the optimum conditions. A hierarchical structure, in which the central controller can be used in the restoration of frequency and voltage when synchronizing the microgrid to the mains, was proposed in [1] and [4]. On the other hand, other solutions were aimed to achieve the power sharing without communications, through the use frequency injection to estimate parameters to compensate for the line impedance effects [3]. However such a technique can compromise the stability of the system and employs complex algorithms to achieve the required compensation.

In this paper, a secondary control loop was implemented in a central controller together with a low bandwidth communications link, to achieve equal sharing of the reactive power between the inverters even when power line mismatches are present. The paper is organized as follows. In Section II, a description of the implemented system was given ranging from the inverter control loops to the complete microgrid setup. Simulation results showing the effect of the power line mismatches on the real and reactive power sharing were also given. Section III contains a description of the secondary control loop that was applied to achieve the reactive power sharing while a summary of the simulation results, showing the suitability of the reactive power sharing algorithm, was given in Section IV.

II. ISLANDED OPERATION OF PARALLEL INVERTERS FORMING A MICROGRID

The islanded microgrid consists of four parallel inverters, each with LC output filters and isolation transformers. A local RL load was connected to the microgrid as shown in the system block diagram in Fig. 1. When the utility grid is present, the static switch (SS) connects the microgrid to the utility grid and handles the synchronization process together with the microgrid central controller (MGCC). For operation in islanding mode, the SS is open and the inverters operate autonomously to regulate the local grid voltage and frequency. A contactor at the output of each inverter allows for synchronization of the inverter via a PLL to the voltage at the PCC, before any power transfer to the microgrid can be

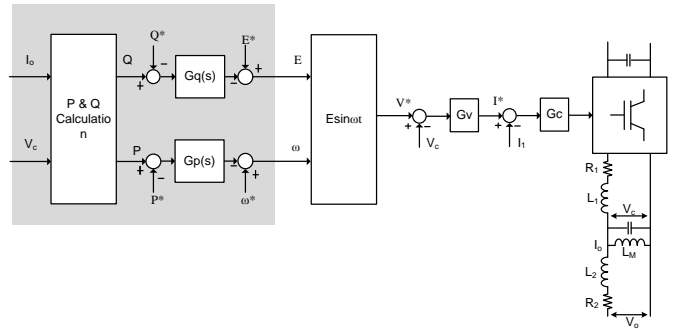


Fig. 2. Microsource Inverter control block diagram for islanded mode.

performed so as to minimize the impact that the inverter has on the rest of the microgrid. The power lines connecting the inverters to the local grid were represented via the short transmission line model.

A. Outer Droop Control Loop

Each microsource inverter is capable of operating in either grid connected or islanded mode depending on the state of the static switch and the presence of the utility grid. For simplicity in this simulation, the state of operation of the microsources is determined by the central controller which also determines the state of the SS. Fig. 2 illustrates the block diagram of the control loop implemented in these inverters that enables operation in islanded mode. In islanded mode, real power is supplied by varying the real power against frequency ($P-\omega$) while in grid connected mode the real power is supplied by varying the real power against the phase ($P-\Phi$), as the frequency is fixed by the grid. The controller evaluates the actual real and reactive power output of the inverter in either mode and sends these values to the droop control algorithm from which the reference voltage waveform is generated. The droop control functions in islanding mode can be mathematically expressed as:

$$\omega = \omega^* - (k_{dP}S + k_{vP})(P - P^*) \quad (1)$$

$$E = E^* - (k_{dO}S + k_{pO})(Q - Q^*) \quad (2)$$

where P is the actual real power output of the microsource; Q is the actual reactive power output of the microsource; k_{pP} and k_{pQ} are the droop gains; and k_{dpP} and k_{dpQ} are the derivative gain terms.

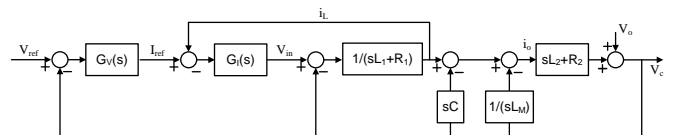


Fig. 3. Block diagram of the inner loops. The plant consists of an LC filter and an isolation transformer to interface with the microgrid. L_M , L_2 and R_2 are the transformer parameters namely the magnetization inductance, leakage inductance and winding resistance. $G_V(s)$ and $G_I(s)$ are the voltage and current controller transfer functions respectively.

B. Inner Control Loop Design

The voltage control loop regulating the inverter output voltage is common for both operation modes. The proposed inner controllers, based on the stationary reference frame, consist of a voltage and an inner current loop. The voltage and current control loops are both based on the Proportional-Resonant (PR) controller [10 - 12]. The PR controller was preferred over the various voltage PID controllers available in literature [9] as the latter have various disadvantages when the control variable is sinusoidal and the controlled variable is not transformed to the synchronous frame. In addition, simulations carried out with the system in Fig. 1 comparing the performance of the PR to a two-degrees of freedom PID have shown superior performance of the PR by achieving a lower voltage THD at the output of the LC filter.

In order to analyze the closed loop dynamics and determine the controller gains required, a linear model of the system was obtained as shown in Fig. 3. V_{ref} is the voltage reference that is obtained from the outer droop control loop, i_L is the current through inductor L_1 , L_1 is the value of the output inductor, R_1 is the parasitic resistance of the output inductor, C is the value of the filter capacitor. Initially the parameters for the current controller $G_I(s)$ are obtained by considering the inner loop shown in Fig. 3 and by using root locus techniques while assuming V_c as constant. The voltage controller parameters can then be obtained by simplifying the block diagram of Fig. 3 and by using root locus techniques. The bode plot of the simulated closed loop system is shown in Fig. 4. The transfer functions of the voltage and current controllers can be given by [10]:

$$G_V(s) = K_{pV} + \frac{2k_{iV}s}{s^2 + 2\omega_{cV}s + \omega^2} \quad (3)$$

$$G_I(s) = K_{pI} + \frac{2k_{iI}s}{s^2 + 2\omega_{cI}s + \omega^2} \quad (4)$$

where K_{pV} and K_{pI} are the proportional gain terms, k_{iV} and k_{iI} are the resonant gain terms, ω_{cV} and ω_{cI} are the resonant bandwidth control terms and ω is the resonant frequency.

C. Simulation Results

The aim of this section is to analyze the effect on the power

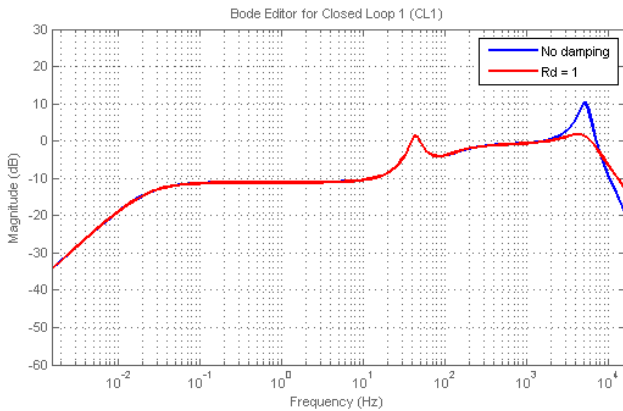


Fig. 4. Bode plot of the closed loop transfer function $\frac{V_c(s)}{V_{ref}(s)}$ with and without a 1Ω damping resistance for the following PR controller parameters: $K_{pV} = 2$, $K_{pI} = 10$, $k_{iV} = 615$, $k_{iI} = 2512$, $\omega_{cV} = 3.14$ and $\omega_{cI} = 31.4$.

sharing capabilities of inverters, employing droop control, due to mismatches in the power line parameters. So as to ensure that any differences that arise between the simulations carried out are due to the differences in power line parameters, identical parameters were used for the inverters connected in the setup shown in Fig. 1. The microsource inverter hardware parameters used in the simulation are: $L_1 = L_2 = 1\text{mH}$, $L_M = 1\text{H}$, $C = 20\mu\text{F}$ and $R_1 = R_2 = 0.2\Omega$. The four inverters, were connected sequentially to the microgrid (at $t = 0\text{s}$, 1s , 2s and 3s respectively) while operating in islanded mode. Inverter 1 is connected at $t=0$ and sets the microgrid voltage and frequency according to the droop control. It is assumed that the inverter can handle the load present on the microgrid. The other inverters synchronize with the microgrid voltage and are connected at 1s intervals. Under these conditions, it is expected that the inverters share equally the active and reactive power demanded by the load.

The voltage control loop, as shown in Fig. 4, exhibits a closed loop bandwidth of 7.7 kHz while resonance due to the output filter was seen to occur at 5.16 kHz when assuming that the filter capacitance has no series resistance component as damping. Fig. 4 illustrates that the gain at the resonant frequency is quite high at 10.4dB. Passive damping techniques can be introduced to reduce the gain at the resonant frequency at the expense of a reduction in the attenuation at higher frequencies. The addition of a 1Ω series resistor reduces the resonant frequency to 4.5 kHz and the resonant gain to 1.83dB. The outer loop parameters were designed so as to achieve minimal variations in E and ω while achieving a fast transient response in regulating both the P and Q . The maximum deviation allowed for ω and E is also determined by the maximum rating of P and Q that the inverter can supply.

1) *Identical Power Line Parameters:* The initial tests set a benchmark of the desired operation even when mismatches are present. This scenario therefore considered identical power line impedances ($R_{TX_n} = 0.035\Omega$ and $L_{TX_n} = 0.011\text{mH}$). The four inverters connected to the microgrid, were connected sequentially while operating in islanded mode and regulation of the local grid voltage and frequency via droop control was then performed. The load current is divided equally between the inverters when their respective output contactor is turned on and steady state is achieved in less than 0.25s. In this case, the inverters share the real and reactive power demand equally according to the load demand, as shown by the feedback plots in Fig. 5 - Fig. 6. At steady state, the real power supplied by each inverter settled to approx. 1085 W while the reactive power supplied by each inverter settled to approx. 347 VAr.

2) *Mismatch in Power Line Parameters:* Mismatches in the parameters of the power lines that connect the inverters to the local grid cause additional voltage drops and phase shifts into the system. For a control system based on voltage and phase differences for decentralized sharing of the real and reactive power such as droop control, one may state that the power sharing is affected by these variations. The power line impedances connecting the inverter models to the microgrid used in this simulation are given in Table I.

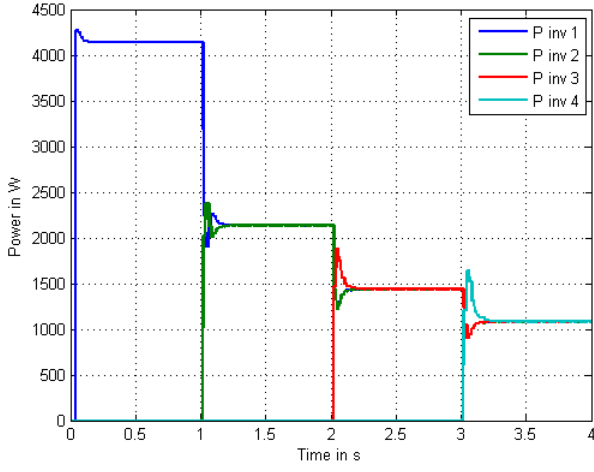


Fig. 5. Real Power Sharing achieved for setup with identical power line parameters.

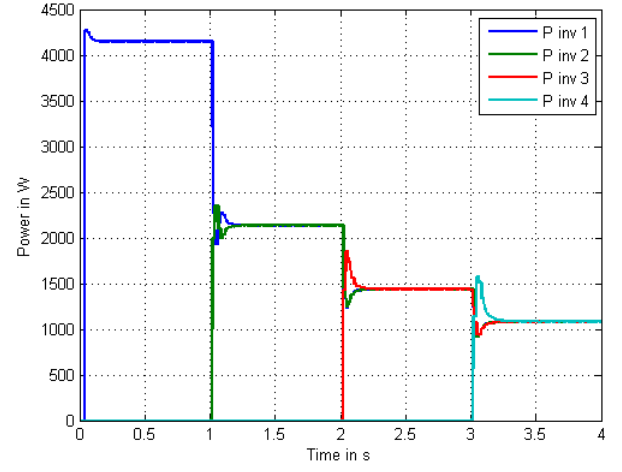


Fig. 7. Real Power Sharing achieved for setup with power line parameter mismatches.

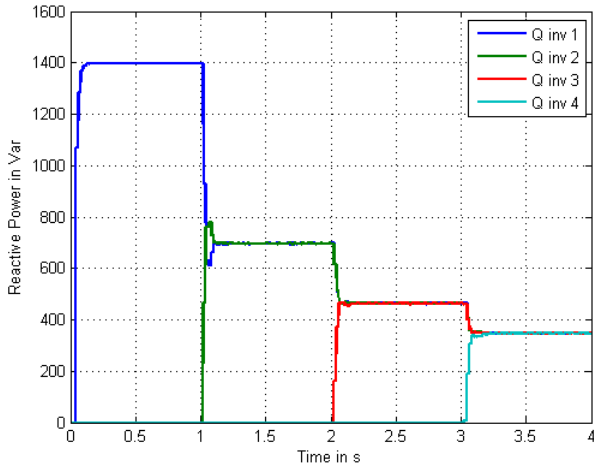


Fig. 6. Reactive Power Sharing achieved for setup with identical power line parameters.

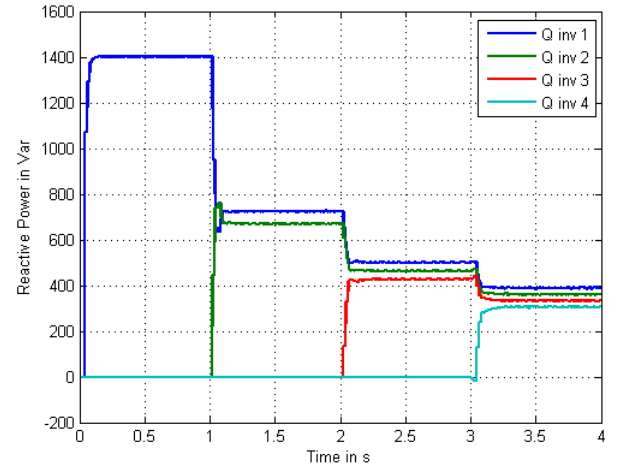


Fig. 8. Reactive Power Sharing achieved for setup with power line parameter mismatches.

The real power transient response when each of the inverters is connected to the microgrid is shown in Fig. 7. The dynamics that were obtained in the case of the real power sharing were identical to the ideal case of equal power line impedances. Hence, the control algorithm is able to compensate for the mismatches in the power line parameters as these did not affect the real power sharing capabilities during operation.

The reactive power transient response when each of the inverters is connected to the microgrid is shown in Fig. 8. In this case, the power line mismatches were seen to affect the reactive power sharing capabilities of the inverters. The reactive power delivered by each inverter was seen to change as the power line impedance was changed. From the simulations performed there were also cases where the inverters were absorbing reactive power as can also be seen in Fig. 8.

The unequal sharing of the reactive power was seen to arise due to mismatches in the instantaneous voltages at the output of the inverters, additional voltage drops and phase shifts due to the different power line impedances. In the

simulations it is assumed that the inverters are not operating at their maximum capabilities while in islanded mode. Otherwise, the sharing of the real power would also be effected when the reactive power sharing becomes unbalanced.

TABLE I. POWER LINE PARAMETERS

| Inverter | Power Line Parameters | |
|----------|-----------------------|------------|
| | $R_{TX,n}$ | $L_{TX,n}$ |
| | Ω | mH |
| 1 | 0.0175 | 0.005 |
| 2 | 0.0350 | 0.011 |
| 3 | 0.0525 | 0.016 |
| 4 | 0.0700 | 0.022 |

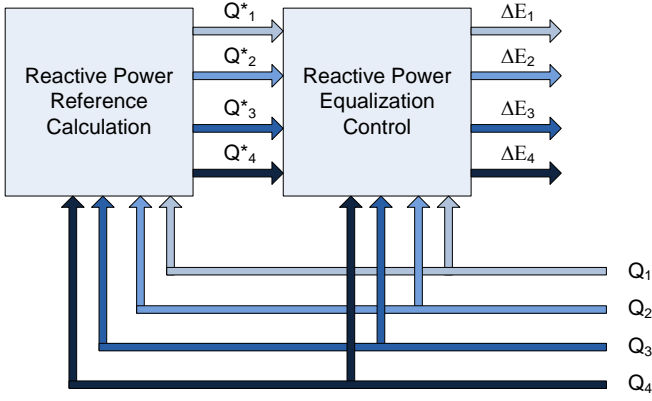


Fig. 9. Block Diagram of Central Controller Algorithm.

III. REACTIVE COMPENSATION LOOP

Achieving equal reactive power sharing between the inverters that are connected to the microgrid is a complex task. The inverters cannot compensate for mismatches in their reactive power outputs while provided only with local voltage and current information, since the operating parameters of the other inverters are unknown. To optimize the operation of the inverters and achieve equal sharing of the reactive power demand, communication via the MGCC must be performed to regulate the reactive power supplied by each inverter connected to the microgrid.

Each of the microsource inverters provides the MGCC information of the reactive power delivered to the microgrid (Q_1 to Q_4 respectively), via a low bandwidth communications link. This link can take various forms as various communications technologies currently exist. The MGCC then determines the amount of reactive power that each inverter should supply and regulates the reactive power of each inverter via a slow external loop. Fig. 9 illustrates the block diagram of the reactive power equalization algorithm implemented in the MGCC while Fig.10 shows how the loop interacts with the control loop of the microsource controllers.

The simulation was carried out for the case of identical inverters and hence knowledge of the droop gains by the MGCC was not required. For the case of non-identical inverters which supply power according to their droop gains, the reactive power demand can be calculated accordingly. However each inverter must transmit the droop gain to the MGCC to enable proper sharing of the reactive power. This is a one-time operation and can be performed during the setup time i.e. when the inverter is connected to the microgrid for the first time. The reactive power demand for each inverter can be calculated by:

$$Q_x^* = \frac{Q_{total}}{n_x \left(\sum_{i=1}^4 \frac{1}{n_i} \right)} \quad (5)$$

where Q_{total} is the reactive power supplied by all the inverters, Q_x^* is the reactive power demand that is required to be supplied by inverter x , n_x is the droop gain of inverter x , and

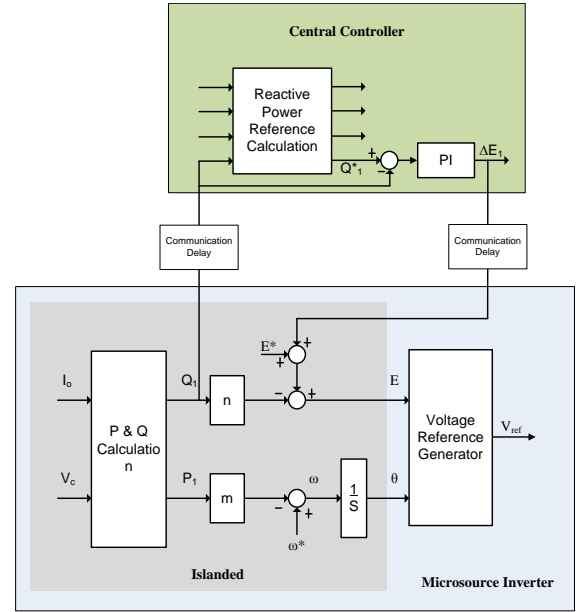


Fig. 10. Block Diagram of a microsource inverter including the additional Central Controller loop that compensates for the reactive power mismatch.

$\sum_{i=1}^4 \frac{1}{n_i}$ is the summation of the droop gains of the inverters connected to the microgrid.

Once the reactive power references are determined, the MGCC regulates the reactive power of each inverter via PI controllers. In this simulation, the PI controllers provide an additional change in voltage that is added to that of the droop control output (ΔE_n). Since a low bandwidth communications link was used, the PI controller was designed such that the closed loop system exhibits a settling time of 0.5s. The settling time can be increased to minimize the communications bandwidth. The parameters for the PI controller are $K_p = 2e-3$ and $K_i = 0.04$ and the corresponding time response is shown in Fig. 11.

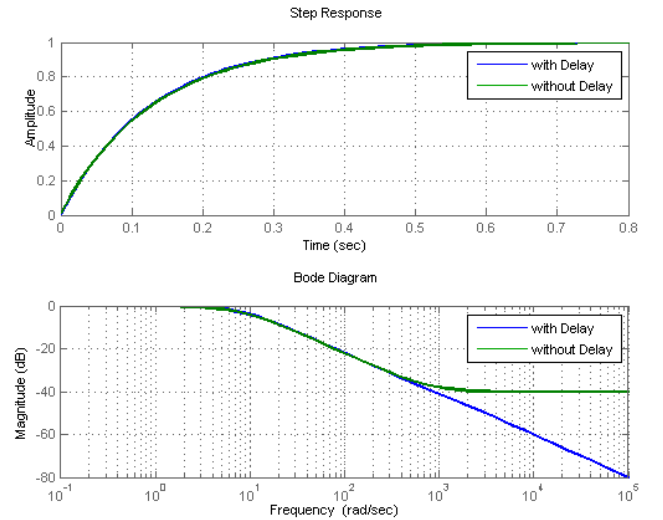


Fig. 11. PI Controller Step Response and Bode Plot of the Closed Reactive Compensation Loop with and without communication delay.

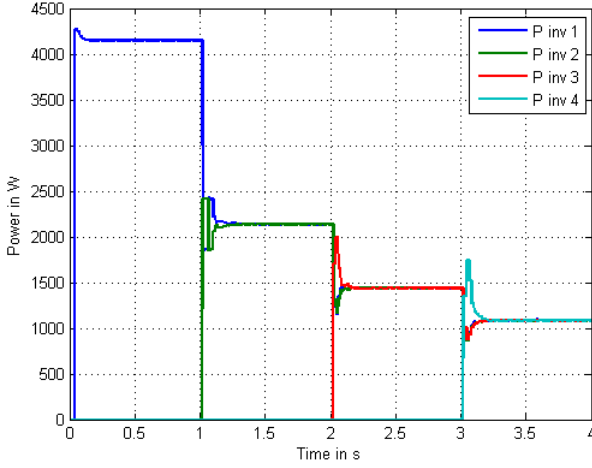


Fig. 12. Real Power Sharing achieved for setup with compensation algorithm including time delays and power line parameter mismatches.

Communication delay effects were also modeled to verify their effect on the compensation algorithm. Delay blocks were added to the simulation model as shown in Fig. 10 and the delay was assumed to be equal to 1ms for each delay block. The delay blocks were modeled using the first linear approximation as:

$$G_d(s) = \frac{1}{T_d s + 1} \quad (6)$$

where T_d is the time delay of each block. From Fig. 11 one can observe that the time delay introduces a negligible effect on the time domain response.

IV. SIMULATION RESULTS

The microgrid setup shown in Fig. 1 was used to simulate the effect of mismatches in the power line parameters connecting the inverters to the local microgrid was modified to include the additional MGCC functionality. Thus the suitability of the MGCC algorithm, described in the previous section, to share equally the reactive power demand can be verified.

The real power transient response when each of the inverters is connected to the microgrid is shown in Fig. 12. When comparing this result to the previous simulations, identical results were obtained hence the introduction of the additional loop regulating the reactive power in the MGCC did not affect the transient characteristics and the real power sharing of the inverters during both transients and steady state operation.

The introduction of the control loop in the MGCC to regulate the reactive power of each inverter, were seen to affect the dynamics of the inverters according to the characteristics of the external loop. At steady state the reactive power supplied by each inverter settled to approx. 347 VAR, as shown in Fig.13. The same results as the simulations without the mismatches were obtained which shows the effectiveness of this algorithm in sharing equally the reactive power between

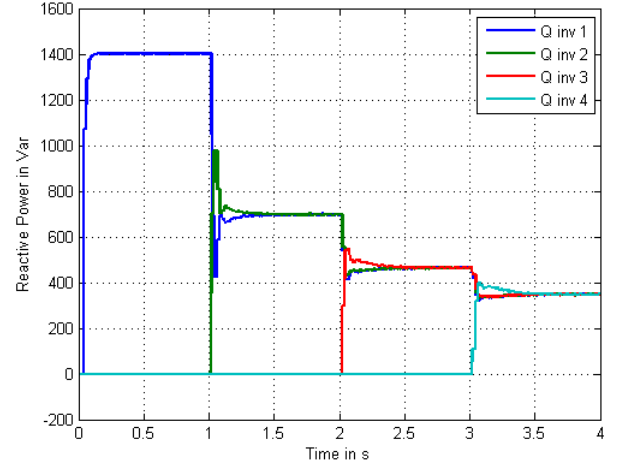


Fig. 13. Reactive Power Sharing achieved for setup with compensation algorithm including time delays and power line parameter mismatches.

the inverters. A settling time of 0.5s can be observed when each inverter was connected to the local grid according to the design criteria specified.

Simulations carried out show that the stability of the compensation loop is not compromised with the additional delays while equal real and reactive power sharing was still achieved with the same settling time as the simulations without delay.

V. CONCLUSIONS

This paper considers the unequal reactive power sharing that occurs due to power line impedance mismatches that occur during islanded mode of operation. A low bandwidth control loop implemented in the central controller, designed to have a settling time of 0.5s, was proposed to achieve equal reactive power sharing between the inverters connected to the microgrid. Simulation results have shown that the proposed system achieves equal reactive power sharing thereby indicating the effectiveness of the algorithm. Additional communications delays between the central controller and the microsources do not affect the reactive power sharing capability of the implemented solution. Simulations carried out have shown that the real and reactive power sharing for non-linear loads is similar to that obtained for linear loads. Hence, the same algorithm implemented in the central controller can also be applied to non-linear loads to achieve equal reactive power sharing.

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